

HIPERCORIG – an innovative hydraulic coring system recovering over 60 m long sediment cores from deep perialpine lakes

Ulrich Harms¹, Ulli Raschke², Flavio S. Anselmetti³, Michael Strasser⁴, Volker Wittig⁵, Martin Wessels⁶, Sebastian Schaller³, Stefano C. Fabbri³, Richard Niederreiter⁷ and Antje Schwalb²

- ¹ Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany
² Institute of Geosystems und Bioindication, Technische Universität Braunschweig, Langer Kamp 19c, 38106 Braunschweig, Germany
³ Institute of Geological Sciences and Oeschger Centre for Climate Change Research, University of Bern, Baltzerstrasse 1+3, 3012 Bern, Switzerland
⁴ University of Innsbruck, Institute of Geology, Innrain 52f, room 6O-305, 6020 Innsbruck, Austria
⁵ Fraunhofer IEG, Lennershofstraße 140, 44801 Bochum, Germany
⁶ Institut für Seenforschung (ISF) der LUBW Landesanstalt für Umwelt Baden-Württemberg, Argenweg 50, 88085 Langenargen, Germany
⁷ UWITEC GmbH, Umwelt und Wissenschaftstechnik, Weißensteinstraße 30, A-5310 Mondsee, Austria

Correspondence to: U. Harms (ulrich.harms@gfz-potsdam.de)

Abstract. The record of past environmental conditions and changes archived in lacustrine sediments serves as an important element in paleoenvironmental and climate research. A main threshold to access these archives is the undisturbed recovery of long cores. In this study, we have developed and tested a new, environmentally-friendly coring tool and modular barge centred around a down-the-hole hydraulic hammering of an advanced piston-corer system, the HIPERCORIG. Testbeds for the evaluation of the performance of the system were the two periglacial Lakes Mondsee and Constance located on the northern edge of the Alpine chain. These lakes are notoriously difficult to sample beyond ~10 m sediment depths due to dense glacial deposits obstructing deeper coring. Both lakes resemble many global lake systems with hard and coarse layers at depth, so that the gained experience using this novel technology can be applied to other lacustrine or even marine basins.

These experimental drilling projects resulted in up to 63 m coring depth and successful coring operations in up to 204 m water depth providing high-quality, continuous cores with 87% recovery. Initial core description and scanning of the 63 m long core from Lake Mondsee and two 20 and 24 m long cores from Lake Constance provided novel insights beyond the onset of deglaciation of the Northern Alpine foreland dating back to ~18.4 ka.

1 Introduction

Many lakes have been identified as outstanding recorders of local, regional, and sometimes even global climate and environment in high resolution and with long-lasting continuity over several glacial-interglacial cycles. These archives cover major parts of the Quaternary (Litt and Anselmetti 2014, Johnson et., 2016, Wagner et al., 2019) and beyond (Brigham-Grette et al., 2013). However, the identification of lacustrine strata bearing highly resolved time series requires studies that show high-quality proxy-data and at the same time radiometric dating possibilities. Such investigations are usually performed on cores (~10-15 m long) that can be recovered using simple and inexpensive gravity or piston-coring devices. In order to access sediment archives with long geological history, hydro-acoustic data (bathymetric and seismic data) need to be acquired to

40 elucidate if such promising strata continue without hiatus to greater depth. The second step is to plan and conduct coring to depths of at least several decameters. This requires in most cases drilling operations conducted with the help of commercial contractors to ensure achieving sediment depths beyond 20 meters or more. Because costs for coring deep, continuous and undisturbed strata from large lakes requires budgets in the range of 1 Million \$, well-developed project proposals often involve complex, lengthy international funding efforts before they can be realized.

Our approach to address the lack in easily available coring techniques to recover up to 100 m long sediment cores was twofold:

- 45 • Design, construct and field-test a novel, high-quality "soft-sediment" coring system that allows penetration beyond today's hand-driven piston corers while remaining economically well below industry coring operations
- Test the new coring system on two lakes whose sediments are known to resist standard coring attempts, which are hitherto unexplored but bear most likely a high scientific value

50 We chose Lake Mondsee in Austria and the trans-boundary Lake Constance in Austria, Germany, and Switzerland (Fig. 1) as a testbed because previous attempts to core deeper than 14 m in these basins failed. At the same time the previously recovered Holocene clay-rich lakebed deposits include a wealth of data on the environmental, climate and hydrologic evolution of these perialpine basins (see e.g., Wessels et al., 1998; Schwalb et al., 2013; Daxer et al., 2018 and references therein, Blattmann et al., 2019).

55 This study is providing insights into the technique of the new coring system named HIPERCORIG ("high percussion coring rig") and its deployment on the test lakes. The core material recovered from up to 63 m depth below lake bottom and in over 200 m water depth is described and first results of core analyses are discussed.

2 Key components and functions of HIPERCORIG

60 HIPERCORIG consists of a highly mobile, modular barge system, a coring rig, a hydraulic piston-coring device, steel casings, lake-bottom ground plate and winches, ropes and other auxiliary equipment that can all be packed and shipped in four 20-ft standard shipping containers (Fig. 2). The platform is 6.3 x 8 m in size, comprising 14 floating tanks of stainless steel of 2, 3 or 4 m x 1 x 1 m dimension. A moon pool (2 x 2 m) in the center ensures centralized lowering of all underwater equipment via the drill rig. The barge is self-propelled by two outboard engines up to a speed of 6 km/h and accompanied by two outboard-engine driven rubber boats, which are also be stored in the containers. The barge has a draft of 30 to 40 cm and its freeboard

65 can be adjusted using four blow ballast tanks according to needs for speedier taxi or wave-action dampening on site.

At coring position, the four Bruce-type anchors are set each on 700 m Kevlar rope outwards from the barge to keep station. Precise stationing and re-adjustment perpendicular over the drill site is achieved with the four hydraulic anchoring winches.

70 Coring operations are prepared by lowering a 4-m-high ground plate through the moon pool with four winged basal plates to the bottom of the lake (Fig. 3). It is applied to ensure a vertical angle of the coring equipment to the lake bottom. Entry for the casing pipe is provided through a 1 x 1 m re-entry cone mounted on top of the base plate.

Hoisting and mounting of the ground plate and all underwater equipment is made using a 7-m-high coring rig. A 46-kW

75 hydraulic aggregate drives all winches and motors. In the following step, 2-m-long pipe sections forming together an up to 70 m long casing are connected with a pipe-spinner rotary unit and are finally topped by an upper re-entry cone. This casing-pipe set up is lowered to the ground plate through the re-entry cone in the right position.

80 Coring preparation starts on the drilling platform by assembling the core-barrel unit, hammer unit and heavyweight pipes, the innovative centerpiece of HIPERCORIG. It is a combination of a hydraulic down-the-hole (DTH) hammer with a well-proven piston-coring system. The water-driven DTH hammer (e.g. Wassara AB), developed originally for deep drilling or mining, is connected to the piston corer with a special adaptor. The key advantage of such DTH hammer is that the force is transferred to the corer directly without dampening effects of drill pipe connectors, when using uphole percussion. Furthermore, by using the lake water instead of oil as hydraulic fluid to drive the hammer, oil spills are excluded and hazard-free operations in fragile lake ecosystems are possible.

90 The 2-m-long coring barrel is tipped by a stainless-steel piston at the lower end (Fig. 4A) and harbors a 90 mm diameter, 2-m-long plastic core liner to ensure high-quality coring success. The DTH hammer (Fig. 4B) and heavy weight rods (2 m, 300 kg) on top ensure that the required weight for percussion momentum is sufficient and directed downwards (Fig. 4C). A high-pressure water pump controls the latter with flow rates of max. 120 l/min and up to 200 bar operating pressure through a reeled hydraulic hose. This hydraulic hose transfers water and hydraulic energy down the hole and is led in parallel to the Kevlar ropes holding the coring unit and allowing additional axial pull forces.

95 Once the piston-coring unit, DTH hammer, and heavyweights are assembled, they are lowered through the moon pool down into the upper re-entry cone (1 x 1 m) on top of the casing pipe that sits in the ground plate. This rigging is controlled online using two underwater cameras mounted to the ground plate. Coring starts when the piston at the end of the core barrel hits the sediment surface. Within the uppermost few meters, the power of its own weight presses the core barrel into the sediment while further down, the hammer produces impulses up to 70 Hz. After 1.85 m, the piston reaches the top of the core barrel where the plastic liner sits. At this position, the piston is locked and the hydraulic pressure in the system activates the core catcher and closes the liner at the end of the core barrel. The sediment-infilled coring unit is then winched up to the platform, the core is retrieved and the unit is cleaned for the next run (Fig. 5). After each core trip, the outer casing pipe sinks down deeper by its own weight or is being pushed or hammered to the depth of the previous core run once compacted sediment is reached. If borehole instabilities occur and sediment narrow the borehole causing stuck casing pipes, a water-jetting cleaning tool within the system is activated to flush the casing pipe free. In addition, a closed piston system was fabricated and tested at Lake Mondsee to be used once the borehole walls remain steady and stabilizing casing is not needed anymore.

An operating staff for coring and initial core handling of at least four persons is required to run HIPERCORIG in coring mode. The assembly or dismantling on shore requires five days work also for a crew of four to five.

3 Test sites, operations and methodology

110 3.1 Lake Mondsee

115 Lake Mondsee is a glacial perialpine lake. Its uppermost sedimentary infill has previously been studied for paleoclimate, paleolimnology and paleoecology since the Bölling/Alleröd interstadials ~14 ka, as covered by several, up to 14-m-long sediment cores retrieved from the deepest part of the lake at ~60 meter water depth (Schultze & Niederreiter, 1990; Lauterbach et al., 2011; Swierczynski et al., 2013; Namiotko et al., 2015; Andersen et al., 2017; Daxer et al., 2018). Reflection seismic data, however, imaged a well-stratified, undisturbed, postglacial sedimentary sequence of at least 60 m thickness (Fig. 6, Daxer et al., 2018), deposited within a rather short time period of ~4-5000 years after the Traun Glacier had retreated from the Mondsee area about 19 ka (Ivy-Ochs et al., 2008; Reitner 2011). This scientific setting thus provided an ideal local test site, moreover, the nearby location of the manufacturers workshops (Uwitec GmbH) in Mondsee village, Austria, eased logistics.

120 Design, building, assembly and acquisition of parts of the HIPERCORIG system were conducted in 2016 and 2017, while
component assembly was performed during fall 2017. A first test of the complete system was conducted from April 16 to
October 1, 2018 near the previous long-coring site by Daxer et al., (2018) at 60 m water depth (47N 48,315; 13E 24,582),
where reflection seismic data image clear coring targets up to 60 m below lake floor (mblf; Fig. 6). The assemblage of all parts
including the barge with all equipment was performed without problems within 6 days. On April 27, the test drive for the
125 nautical certificate ("Schiffahrtstechnisches Gutachten") was achieved successfully.

After anchoring and site setup, a first adaptation of the coring process and platform layout was necessary. While it was
originally planned to use the casing pipes with a re-entry cone for the coring device on top, it turned out that it was possible to
connect the casing pipes directly from the lake bottom to the platform without re-entry funnel in water depths below 60 m.
130 With this adaptation, the ground plate was assembled, lowered to lake floor and connected with the casing and core-barrel unit
by Kevlar ropes to the platform. As cameras, tilt sensors and the remote control of the casing brackets worked perfectly,
sediment coring begun on May 9, 2018. Because of its own weight, the casing pipe sunk to the depth reached after each core
retrieval up to 10 mbfl. Consequently, hole reaming after every 2 m core section was not necessary. At a depth of 26 mbfl,
operations were halted to solve constructional issues including wear-free seals and a new twist-proof construction of the entire
135 DTH. In addition, dismantling of the entire 86 m (26 m sediment depth plus 60 m water depth) casing pipe was needed to
control the crown seal.

During the operational pause, the platform moved slightly away from the ground plate by wave action so that it was not possible
to re-entry into the ground plate. In order to avoid such shifts during future operations, a best practice was developed to correct
140 the position with the anchor winches using the inclination sensors. From late June 2018 on, coring commenced from a
minimally offset position (Hole B) from 20 to 30 m depth after displacing in non-coring mode the upper 20 m. After coring in
Hole B continued from 28 mbfl, it took 4000 strokes to reach 30 mbfl and 4 t traction was needed to pull out the coring
assembly and the casing could neither be progressed nor retrieved. Consequently, it was necessary to invent a new method to
continue coring without casing pipe. For this purpose, the end piece of the coring chamber was modified so that the piston was
145 hydraulically locked using a valve until the core filled the chamber and locking could be released. This modification allowed
to reach 52 mbfl coring depth in Hole B (termed section C in Fig. 7). Further tests with different diameter coring (63 and 90
mm) below 52 mbfl coring depth (termed section D) in Hole B were conducted in September 2018 to finally reach 63 mbfl
total coring depth.

150 The cores retrieved were sealed with end caps in the 2-m-long, clear plastic liners and marked on board before they were stored
at ambient temperature at Uwitec Mondsee, before they were transported, curated and further analyzed in the Austrian Core
Facility (ACF) at the University of Innsbruck. Overall core recovery, as calculated from effective length of sediment-filled
core liners compared to the actual penetration advance of the bit (Fig. 7), ranged between 82 and 78% for Hole A and B,
respectively. Apart from the coring intervals with technical challenges, as described above, where core recovery dropped to
155 50%, most coring advances achieved nearly 90% of core recovery. This slightly reduced recovery is due to a systematic loss
of core of about 15 cm at the bottom of each run.

At the ACF, cores were further cut in 1 m whole-round segments and measured for physical properties (bulk density, p-wave
velocity and magnetic susceptibility) at 0.5 cm resolution using a GEOTEK Multi-Sensor Core Logger (MSCL). Selected core
160 segment representing different lithofacies, as interpreted from MSCL data (see section 4.1) were split, line-scan photographed,
described and sediment from the lowermost core section between 62.0 and 62.8 mbfl was sieved to sample terrestrial leaf
fragments and cuticles of macro-remains for AMS 14C analysis at the Ion Beam Physics Laboratory of ETH Zürich (ages
presented here are calibrated using the IntCal13 calibration curve (Reimer et al., 2013)). Furthermore, and for assessing core

quality and lithology in 3D, selected core segments were also scanned for X-ray computed tomography (CT) using a Siemens SOMATOM Definition AS at the Medical University of Innsbruck with a voxel size of 0.2 x 0.2 x 0.3 mm³. Unopened core sections remain stored at 4°C at the ACF awaiting further scientific analyses.

3.2 Lake Constance

The lacustrine infill of Lake Constance carries distinctive paleoenvironmental signals (Wessels 1998, Schwalb et al., 2013), which so far could only be recovered from the upper ~11 m thick sediments although more than ~100 m infill has been interpreted from seismic data (Müller and Gees, 1968). New surveys indicate even up to 250 m of Quaternary sediments (Fabbri et al., 2018). The well-defined and horizontally bedded lacustrine sediments of the upper tenth of meters were thought to be most likely Holocene deposits that overlay deeper undisturbed Late Glacial sediments. In order to shed new light on the lake as paleoenvironmental archive and to test HIPERCORIG in deep lake waters, a second HIPERCORIG test-drilling campaign took place from May to July 2019 on Lake Constance. Site selection was based on a new reflection seismic profiling campaign from 2017 with focus on the up to 250 m deepest part of the lake (Fabbri et al., 2018, Fig. 6B). A site located ~2 km SW of Hagnau, Germany (Fig. 6B) was selected based on seismically undisturbed and at least 100 m deep strata in 204 m water depth off ferry routes and underwater cables but close to a harbor.

The coring campaign began on May 13, 2019 with the set-up of HIPERCORIG in Langenargen harbor, 20 km East of Hagnau. The platform was taxied on May 22nd after a weather delay to the preselected position for dropping of the four anchors (Fig. 6). The platform was winched precisely on site and the ground plate was lowered to the lake floor in 204 m water depth. The casing was connected on the next day but sank without control due to a failure of the casing winch; it hit the ground plate and damaged the re-entry cone. Using an ROV deployment with R/V Kormoran of the ISF on May 28th, 2019 the damage was inspected via video and the ground plate recovered. On June 5rd, 2019 the ground plate was replaced with repaired re-entry cone before new casings were assembled and set so that coring Hole A could begin. The first five core runs to 10 m depth were piloted smoothly through clay-rich sediments. Below a depth of ~10 mblf, sandy intercalations prevailed requiring disassembling of the coring system for cleaning after each coring run. Additionally, sand intrusions in the lowermost part of the hole choked the casing pipe. After each core recovery, a cleaning run was necessary to reach the depth of the previous core. On June 13th, a depth of 24 mblf was reached with a total recovery of 80% (Fig. 7), when the coring unit got stuck within the casing pipe due to sand accumulations in the annulus. In order to avoid future wedged coring device in the casing, a reverse-circulation mode for the water outflowing from the hammer was built during an operational break. During this break a thunderstorm with >100 km/h gusts slackened one of the anchors, displaced the platform 12 m away from the ground plate and bend some casing pipes. The hole was not accessible anymore so that the casing pipe and the ground plate had to be dismantled.

The second hole, Hole B, ~10 m away from the original location, was started on July 3, 2019 at 0.5 mblf depth to create core overlap to the first hole. Coring to 10.5 mblf proceeded without any problems until sediments became sandy again and cleaning the coring device and the well from the mobilized sand became necessary as in the Hole A. Coring continued with slightly slower progress and total 87% core recovery to a depth of 20.5 mblf, when on July 8th, a shackle failure in the rig caused a loss of the coring assembly. On July 9th, the situation under water was inspected using again the R/V Kormoran ROV. On July 10th, the ground-plate unit and casing pipe were pulled on board, dismantled and Hole B was abandoned. Finally, three 2-m-long surface cores were taken to have a undisturbed sediment-water interface and, a day later, all the remaining parts and the anchors were pulled and the barge was driven back to Langenargen harbor. Within five days, the entire system was demobilized and packed into the four containers for shipping. A total of 21 core runs produced 42 m of core and demonstrated HIPERCORIG's capability to access deep, coarse and severely compacted lake sediments.

The cores retrieved were sealed with end caps in the 2-m-long, clear plastic liners, marked and curated on board. Packed into thermo-boxes and cooled with ice, they were brought directly by boat to the microbiology labs of the University of Constance to minimize degradation or loss of volatiles. In the labs the liners were cut into 1-m-long sections. First small samples were taken for methane and DNA-measurements before the liners were sealed again and stored at 4 ° C. After the end of the field campaign, all cores were transported to the Institute of Geological Sciences at University of Bern. MSCL core logging, core opening, initial core description and the sampling party were held in Bern in October 2019. From the marking on the barge on, all data were entered into the new drilling information software mDIS of the ICDP (Behrends et al., 2020) following the guidelines of international lake-drilling projects in ICDP. This was the first application of mDIS in a field campaign and served as blueprint for future ICDP projects.

4. Initial core description, measurements and results

4.1. Lake Mondsee

The upper 10 m of the cored lacustrine stratigraphic succession in Lake Mondsee is composed of faintly laminated sediment (the dominant lithology is authigenic micritic carbonate and diatoms with little to no detrital grains) with abundant organic material (revealing rather low-density values $<1.4 \text{ g/cm}^3$) and intercalated layers of high detrital input (characterized by elevated magnetic susceptibility (MS) values). Distinctly lower MS values around 10 mblf and the rather sharp downcore increase in bulk density from 1.4 to 1.9 g/cm^3 between 10 and 15 mblf (Fig. 7), match well with the previously-reported physical properties across the Late Glacial – to – Holocene transition from denser mixed detrital to lower-density authigenic carbonate with intercalated calcitic detrital layers lithofacies (Daxer et al., 2018; Lauterbach et al., 2011). XCT data of cores from these upper 15 m reveal abundant gas cracks (Fig. 8) and core disturbances (the latter due to core handling and non-cooled storage of the gassy organic-rich postglacial sediment cores), which also explains the lack of reliable p-wave velocity data in the upper coring interval (Fig. 7).

Below 15-20 mblf, XCT data reveal excellent core quality (with only minimal deformation-drag along and liner wall and no evidence for any coring-induced flow structures in sand layers). The cored succession is composed of late-glacial laminated detrital carbonates with cm-scale fine-grained calcitic turbidites with silicilastic components, intercalated yellowish detrital layers (poorly sorted medium-sized silt), occasional dropstones and soft-sediment deformation structures (Fig. 8). Density value remain rather constant at $\sim 2 \text{ g/cm}^3$, while p-wave velocities increase constantly with depth from about 1500 to 1650 m/s. Distinct layers showing peaks 2 to 5 times higher than the general background values of $8 \times 10^{-8} \text{ m}^3/\text{kg}$ corrected mass-specific MS, occasional occur throughout, but are more abundant between 20-26 mblf. This coring interval correlates to seismic unit 3 by Daxer et al. (2018), interpreted as a phase of increased erosion in the hinterland possibly linked to the Gschnitz stadial / H1 Heinrich event.

Below 52 mblf, MSCL data are reported with caution because the smaller diameter and partially-opened / dried-out core conditions are likely to have influenced the higher density values of up to 2.3 cm^3 and p-wave values up to 1700 m/s (Fig. 7). The sediment, however, also differs in this lowermost cored succession, and is composed of mixed late-glacial laminated detrital carbonate and up-to-dm-thick fine-grained turbidites. There are distinct localized high-density, conjugated deformation features (Fig. 8), which cannot be explained by coring artefacts. Instead they show that the sediment was compressed, possibly by glacio-tectonic process, and which would explain the higher density and p-wave values as measured by MSCL.

The radiocarbon age from small leaf fragments and cuticles of macro-remains obtained from sieving the sediment of the lowermost 50 cm of cored interval (sample ETH-105425; 62.3-62.8 mbsl; C14 age: 15142 \pm 41 yr BP) reveals a calibrated (95.5% probability) age of 18567-18261 cal yr. BP. This age is well within the range of dated deglaciation of the region (19 \pm 1 ka; Ivy-Ochs et al., 2008; Reitner 2011) and supports the lithology-based core interpretation that HIPERCORIG reached glacial sediments and, thus, recovered a complete lacustrine sedimentary succession since the deglaciation of the Mondsee region. The new Mondsee record, unravelled by HIPERCORIG, represents one of only few having actually sampled and dated an undisturbed sedimentary sequence since the deglaciation in the Alpine foreland (c.f. Zübo core, Lister et al., 1988). The record comprises a 50 m-thick, high-resolution Late glacial sedimentary succession (average sedimentation rate 1,25 cm/year) that was deposited within 4 thousand years(?) after deglaciation), which so far was not reached by conventional coring techniques.

4.2. Lake Constance

The average recovery of 80 and 87% in Holes A and B, respectively, allowed to construct a gapless composite section from the lake bottom downcore to 14.5 m composite depth (mcd). Below, down to 24,01 m final composite depth, four intervals ranging in thickness between 13 and 40 cm were not recovered representing minor gaps in the section. This longest ever recovered sedimentary succession from Lake Constance allows a novel look into the paleoenvironmental evolution of the lake well back into the Late Glacial epoch. Core quality is high, with minor disturbances usually in the uppermost 20-30 cm of each 2 m run, in particular in the softer upper part of the section. The coring system was able to fully recover lithologies that are usually challenging for any coring technique. These include intercalations of cm-scaled coarse sand layers with laminated silty intervals or meter-thick sand units, that all were recovered without evident disturbances (Fig. 8).

A previously studied core collected at a site nearby reached a depth of 8.7 m (BO97/14; Wessels 1998; Hanisch et al., 2009; Schwalb et al., 2013). Comparing the MSCL-density curve of the new core with the porosity curve of the former core suggests that sedimentation rate is a bit higher at the new site. The bottom of the 8.7 m long former core with a basal age of \sim 17'000 yr cal BP may correlate to the new core at \sim 12 mcd (Fig. 7; Schwalb et al., 2013). The lithologies from the surface to that depth can be correlated to various lithologic units described in these previous studies, ranging from brown-gray laminated muds in the uppermost meters (surface core, Fig. 8) to underlying carbonate-rich tan and laminated marls (Core A-3-1; Fig. 8), both representing the Holocene section (Wessels, 1998). Densities in this upper part of the core ranges between 1.3 and 1.5 g/cm³ with few coarse-grained and graded layers reaching up to \sim 1.8 g/cm³ (Fig. 7). Noteworthy is the recent upcore increase in organic matter towards the surface with dark blackish colors reflecting the anthropogenic eutrophication signal (surface core, Fig. 8) (Wessels, 1998; Wessels et al. 1999, Blattmann et al- 2020).

These Holocene units are underlain by massive (density up to \sim 2.1 g/cm³) detrital mud with occasional sand layers (Core B-5-2; Fig. 8) deposited during the Younger Dryas and by finely laminated yellow-brown to gray clayey silt dating further back into the Late Glacial containing alternating layers of yellow loess and grey melt-water deposits (Niessen et al. 1992, Wessels, 1998). From there downcore (i.e. from \sim 12-24 mcd), the recovered lithologies represent a previously unstudied succession that is currently not dated. Sediments consist of layers of structureless coarse sand that may reach bed thicknesses of over one meter with density values partly over 2.2 g/cm³ (Fig. 7). These sands are intercalated by fine-grained and laminated silty sections up to few dm-thickness consisting of numerous graded mm-to cm-scaled layers (Core B-8-2; Fig. 8). These lithologies represent typical depositional processes in periglacial or proglacial lake-near deltas that occasionally provide high-energy underflows delivering sand even to these water depths of over 200 m. The laminated finer-grained graded layers, in contrast, likely reflect deposition away from active channels and presumably have lower sedimentation rate. The site most probably

represents an initial stage of the evolving lake as described elsewhere (Wessels 1998, Schwalb et al. 2013), but with a high proportion of riverborne sand – reflecting the interplay of the lake with its local catchment during the late glacial period.

5. Discussion

290 Motivated by the lack of cost-effective, deep, continuous and high-quality coring capabilities in unconsolidated sediments, our primary technological goal of this study was to develop and test a new system that meets these requirements. Although various coring devices have been deployed (Leroy and Colman, 2001) in the past, recent experiences in the framework of ICDP have shown (e.g. Russell et al., 2016) that for lake sediment thicknesses in the 100 m range, no vital alternative to commercial wireline drilling operations exist so far. Therefore, our goal was to provide a system with a number of key objectives discussed
295 below.

The primary ambition to overcome the usual 20 to 30 m coring limit (although exceptional soft sediments in special cases allow coring deeper, e.g. Mingram et al., 2007) was very well achieved and previous attempts to core deeper in Lakes Mondsee and Constance were convincingly outnumbered. In addition, the penetration of hard layers was successfully performed in the
300 stiff glacial sediments of Lake Mondsee and the massive sand intercalations of Lake Constance. This holds high promises for future drilling campaigns in e.g. turbiditic or volcanic ash layers as well. However, these achievements needed additional technical modifications such as a sand cleaning tool and reverse circulation water-flow for jetting the annulus free from sand that added complexity to HIPERCORIGs operations. Observations using the ROV showed, that hydraulic hammering and pumping of large volumes of water had only negligible effects on the lake floor and did not lead to large plumes of turbid
305 water which might affect sensitive organisms.

The target depth of 100 m coring penetration has not been achieved, however, the 63 m total depth reached provide an excellent prospect to match the initial goal in a variety of sedimentary basins. Nevertheless, future HIPERCORIG projects still need to tackle this challenge. On the other hand, operations in 204 m water depths were performed despite major challenges. The
310 strong water currents in Lake Constance caused deviations of the coring system from the ground-plate that call for control of re-entry via either ROV or an additional upward-looking underwater camera at the re-entry cone. A concept for using the re-entry cone and ground-plate system for geophysical wireline logging has been developed but could so far not be tested and awaits deployment in future missions.

315 Core quality and continuity is as convincing as with other well-proven modern coring systems while the perseverance to hitherto inaccessible depths is very convincing. However, it must be clearly noted that there is a limit of core recovery due to the inevitable loss of core catcher material at the lower end of the corer and therefore approximately 90% core recovery is a realistic upper limit. The way to achieve full coverage is double coring with a second hole at the same drill site. This remains to be an immense cost and time factor, as it is for all other systems at this point. However, the effective costs of operating
320 HIPERCORIG at Lake Constance were a factor of ten times lower than comparable wireline-coring operations in similar environments and provide consequently an outstanding opportunity for cost effective coring of unconsolidated deposits. The limitations of HIPERCORIGs operational range as experienced with the experiments in the two perialpine lakes are that i) strongly compacted sediment layers over several tens of meters are a limit, ii) strong wave actions over 1 m and winds over 8 Bt require halt of operations with temporary evacuation.

325 6. Conclusions

HIPERCORIG is a novel high-quality soft-sediment coring system whose performance has been demonstrated on perialpine lakes in over 200 m water depths and more than 60 m coring depth of lacustrine and glacial sediments. It offers promising

330 prospects for similar environments including targets in shallow marine environments. The new Mondsee core, obtained by
HIPERCORIG, represents the first core that sampled without extensive commercial drilling efforts a complete and undisturbed
sedimentary sequence since the deglaciation of the Alpine foreland. It also allowed recovery of material for radiometric dating
and framing the age of deglaciation of the Mondsee Region to 18.4 +/- 0.15 ka. The new Lake Constance core comprises
Holocene laminated muds and marls underlain by massive detrital muds and intercalated sand layers of the Younger Dryas
and alternating finely laminated silt, loess and melt-water deposits from the Oldest Dryas. This is underlain by previously
335 unsampled thick coarse sand beds and intercalated fine silts showing a dynamic distal delta development adjacent to an Alpine
glacier.

Acknowledgements

We are grateful for financial support of the Deutsche Forschungsgemeinschaft (SCHW 671/19-1, BR 3573/3-1, Project#
290492639) and the German Scientific Earth Probing Consortium GESEP to build and test HIPERCORIG. We deeply
appreciate the dedicated work of the Uwitec staff for building HIPERCORIG and conducting operations. Administrative and
340 logistical support for the Lake Constance operations were provided by Landratsamt Bodenseekreis, Schifffahrtsamt in
Friedrichshafen and Hagnau Community. We would also like to thank Anja Griebner for MSCSL-measurements of Mondsee
cores at the Austrian Core Facility Innsbruck and Christoph Daxer for sampling material for radiocarbon dating and
discussion of Mondsee data, results and interpretation.

References

- 345 Andersen, N., Lauterbach, S., Erlenkeuser, H., Danielopol, D. L., Namiotko, T., Hüls, M., Belmecheri, S., Dulski, P. Nantke,
C., Meyer, H., Chaplignin, B., von Grafenstein, U. and Brauer, A., 2017. Evidence for higher-than-average air temperatures
after the 8.2 ka event provided by a Central European $\delta^{18}O$ record. *Quaternary Science Reviews*, 172, 96–108, doi:
10.1016/j.quascirev.2017.08.001
- Behrends, K., Heeschen, K., Kunkel, C., and Conze, R., 2020. The mobile Drilling Information System (mDIS) for core
350 repositories, EGU General Assembly 2020, Online, 4–8 May 2020, doi: 10.5194/egusphere-egu2020-13663.
- Blattmann, T., Lesniak, B., García-Rubio, I., Charilaou, M., Wessels, M., Eglinton, T.I., and Gehring, A.U. (2020):
Ferromagnetic resonance of magnetite biominerals traces redox changes, *Earth and Planetary Science Letters*, 545, 11640, doi:
10.1016/j.epsl.2020.116400.
- Daxer, C., Moernaut, J., Haas, J., Strasser, M., and Taylor, T. (2018). Late Glacial and Holocene sedimentary infill of Lake
355 Mondsee (Eastern Alps, Austria) and historical rockfall activity revealed by reflection seismics and sediment core analysis.
Austrian Journal of Earth Sciences. 111. 111-134, doi: 10.17738/ajes.2018.0008.
- Fabbri S. C., Allenbach, R., Herwegh, M., Krastel, S., Lebas, E., Lindhorst, K., Madritsch, H., Wessels, M., Wielandt-Schuster,
U., and Anselmetti F.S. 2018. Bedrock structure, postglacial infill and neotectonic fault structures in Lake Constance. 16th
Swiss Geoscience Meeting, Bern 2018.
- 360 Hanisch, S., Wessels, M., Niessen, F., and Schwalb, A., 2009. Late Quaternary lake response to climate change and
anthropogenic impact: biomarker evidence from Lake Constance sediments. *J. Paleolim.* 41, 393-406.
- Ivy-Ochs, S., Kerschner, H., Reuther, A., Preusser, F., Heine, K., Maisch, M., Kubik, P. W., and Schlüchter, C., 2008.
Chronology of the last glacial cycle in the European Alps. *Journal of Quaternary Science*, 23/6–7, 559–573, doi:
10.1002/jqs.1202

- 365 Johnson, T., Werne, J., Brown, E. et al. A progressively wetter climate in southern East Africa over the past 1.3 million years. *Nature* 537, 220–224 (2016), doi: 10.1038/nature19065
- Lauterbach, S., Brauer, A., Andersen, N., Danielopol, D. L., Dulski, P., Hüls, M., Milecka, K., Namiotko, T., Obremska, M., Von Grafenstein, U., 2011. Environmental responses to Lateglacial climatic fluctuations recorded in the sediments of pre-Alpine Lake Mondsee (northeastern Alps). *Journal of Quaternary Science*, 26/3, 253–267, doi: 10.1002/jqs.1448
- 370 Leroy, S.A.G., Colman, S. M., 2001. Coring and drilling equipment and procedures for recovery of long lacustrine sequences. In: *Tracking Environmental Change Using Lake Sediments, Volume 1: Basin Analysis, Coring, and Chronological Techniques*. Last, W. M. and Smol, J. P. (Eds.), Kluwer, Dordrecht, The Netherlands
- Lister G.S. 1988 A 15,000-year isotopic record from Lake Zurich of deglaciation and climatic change in Switzerland: *Quaternary Research*, v29, p. 129-14, doi: 10.1016/0033-5894(88)90056-7
- 375 Litt, T., and Anselmetti, F.S., 2014, Lake Van Deep Drilling Project PALEOVAN, *Quaternary Science Reviews* 104. 1-7.
- Melles M., Brigham-Grette J., Minyuk P., Koeberl C., Adreiev A., Cook T., Fedorov G., Gebhardt C., Haltia-Hovi E., Kukkonen M., Nowaczyk N., Schwamborn G., Wennrich V., and the El'gygytgyn Scientific Party. 2011. The Lake El'gygytgyn Scientific Drilling Project – Conquering Arctic challenges through continental drilling. *Scientific Drilling* 11:29-40
- 380 Melles, M., Brigham-Grette, J., Minyuk, P., Nowaczyk, N. R., Wennrich, V., DeConto, R.M., Anderson, P.M, Andreev, A.A., Coletti, A., Cook, T.M., Haltia-Hovi, E., Kukkonen, M., Lozhkin, A.V., Rosen, P., Tarasov, P., Vogel, H., Wagner, B. 2012. 2.8 Million Years of Arctic Climate Change from Lake El'gygytgyn, NE Russia. *Science* 337, 315-320
- Mingram J, Negendank JF, Brauer A, Berger D, Hendrich A, Köhler M, Usinger H. 2007. Long cores from small lakes—recovering up to 100 m-long lake sediment sequences with a high-precision rod-operated piston corer (Usinger-corer). *Journal of Paleolimnology*, 37: 517-528
- 385 Müller, G., Gees, R.A., 1968. Origin of the Lake Constance Basin. *Nature* 217, 836-837
- Namiotko, T., Danielopol, D. L., von Grafenstein, U., Lauterbach, S., Brauer, A., Andersen, N., Hüls, M., Milecka, K., Baltanás, A., Geiger, W., Belmecheri, S., Desmet, M., Erlenkeuser, H. and Nomade, J., 2015. Palaeoecology of late glacial and Holocene profundal Ostracoda of pre-Alpine lake Mondsee (Austria) - A base for further (palaeo-) biological research. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 419/1, 23–36, doi: 10.1016/j.palaeo.2014.09.009
- 390 Niessen, F., Lister, G. and Giovanoli, F., 1992. Dust transport and palaeoclimate during the oldest Dryas in Central Europe - implications from varves (Lake Constance). *Climate Dynamics*, 8: 71-81.
- Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Ramsey, C. B., Buck, C. E., Cheng, H., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Haflidason, H., Hajdas, I., Hatté, C., Heaton, T. J., Hoffmann, D. L., Hogg, A. G., Hughen, K. A., Kaiser, K. F., Kromer, B., Manning, S. W., Niu, M., Reimer, R. W., Richards, D. A., Scott, E. M., Southon, J. R., Staff, R. A., Turney, C. S. M. and van der Plicht, J., 2013. IntCal13 and Marine13 Radiocarbon Age Calibration Curves 0–50,000 Years cal BP. *Radiocarbon*, 55/4, 1869–1887, doi: 10.2458/azu_js_rc.55.16947
- Reitner, J. M., 2011. Das Inn-gletschersystem während des Würm-Glazials. In: *Arbeitstagung der Geologischen Bundesanstalt 2011 – Achenkirch* (pp. 79–88), doi: 10.13140/RG.2.1.3754.1520
- 400 Russell, J. M., Bijaksana, S., Vogel, H., Melles, M., Kallmeyer, J., Ariztegui, D., Crowe, S.A., Fajar, S.J., Hafidz, A., Haffner, D., Hasberg, A.K.M., Ivory, S.J., Kelly, C., King, J.W., Kirana, K.H., Morlock, M.A., Noren, A., O'Grady, R., Ordóñez, L., S, 2016. *Scientific Drilling* 21, 29-40, doi:10.5194/sd-21-29-2016
- Schultze, E. and Niederreiter, R., 1990. Paläolimnologische Untersuchungen an einem Bohrkern aus dem Profundal des Mondsees (Oberösterreich). *Linzer Biologische Beiträge*, 22/1, 213–235

- 405 Schwalb, A., Dean, W.E., Güde, H., Hanisch, S., Sobek, S., Wessels, M., 2013. Benthic ostracode $\delta^{13}\text{C}$ as sensor for early
Holocene establishment of modern circulation patterns in Central Europe. *Quaternary Science Reviews* 66, 112-122. Doi:
10.1016/j.quascirev.2012.10.032
- Swierczynski, T., Lauterbach, S., Dulski, P., Delgado, J., Merz, B., & Brauer, A., 2013. Mid- to late Holocene flood frequency
changes in the northeastern Alps as recorded in varved sediments of Lake Mondsee (Upper Austria). *Quaternary Science*
410 *Reviews*, 80, 78–90, doi: 10.1016/j.quascirev.2013.08.018
- Wagner, B., Vogel, H., Francke, A. et al., 2019. Mediterranean winter rainfall in phase with African monsoons during the past
1.36 million years. *Nature* 573, 256–260, doi: 10.1038/s41586-019-1529-0
- Wessels, M., 1998. Natural environmental changes indicated by Late Glacial and Holocene sediments from Lake Constance,
Germany. *Palaeogeography, Palaeoclimatology, Palaeoecology* 140, 421-432
- 415 Wessels, M., Mohaupt, K., Kümmerlin, R. and Lenhard, A. (1999): Reconstructing Past Eutrophication Trends from Diatoms
and Biogenic Silica in the Sediment and the Pelagic Zone of Lake Constance, Germany. - *J. Paleolimnol.* 21:171-192.

420

425

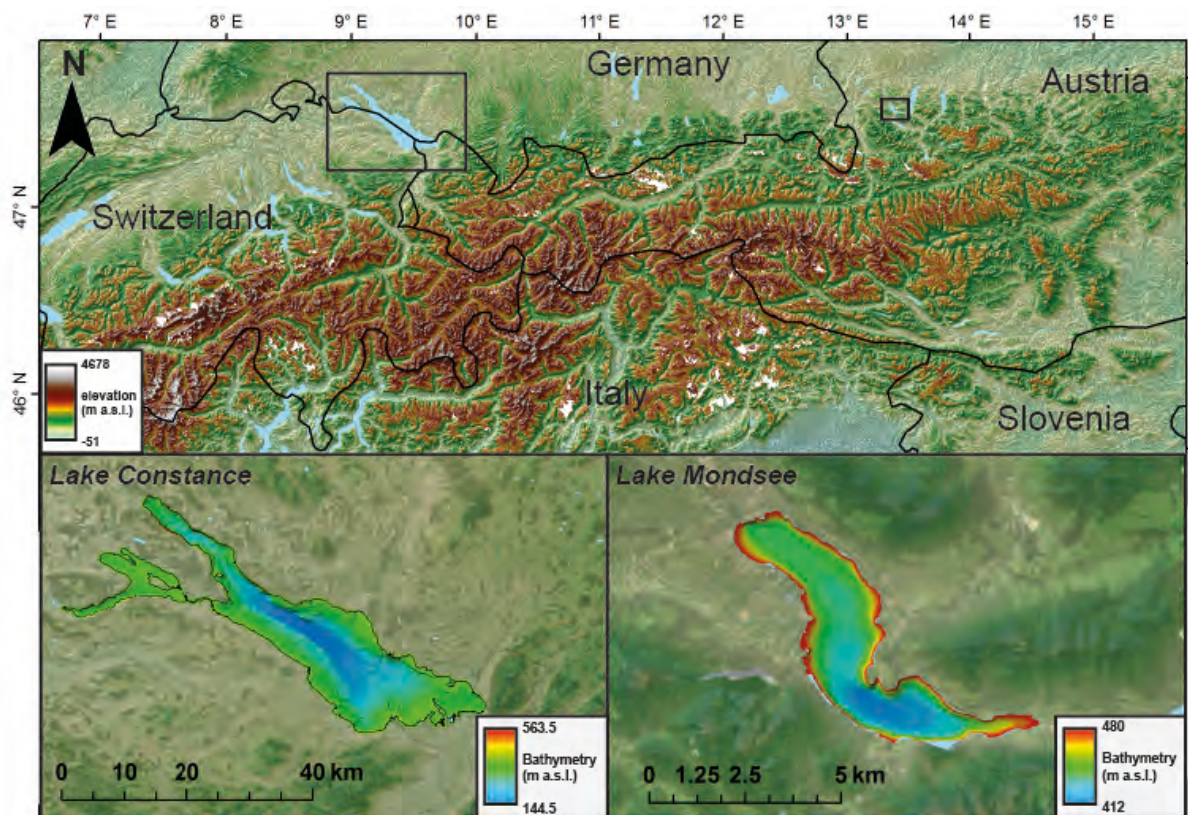


Figure 1: Digital elevation model map of the Alpine chain in Central Europe based on SRTM 1 arc-second imagery (30 meters, USGS Explorer) with borders as solid black lines and all major lakes in blue. Insets show Lakes Constance (Wessels et al., 2015, bathymetry and offshore lidar) and Mondsee with bathymetric information (data courtesy Mondsee bathymetry to I. Trinks, Vienna) superimposed using UTM coordinates. The inset maps combine elevation data with topographic maps (orthographic aerial and satellite imagery from Bing maps, Microsoft Corp.).

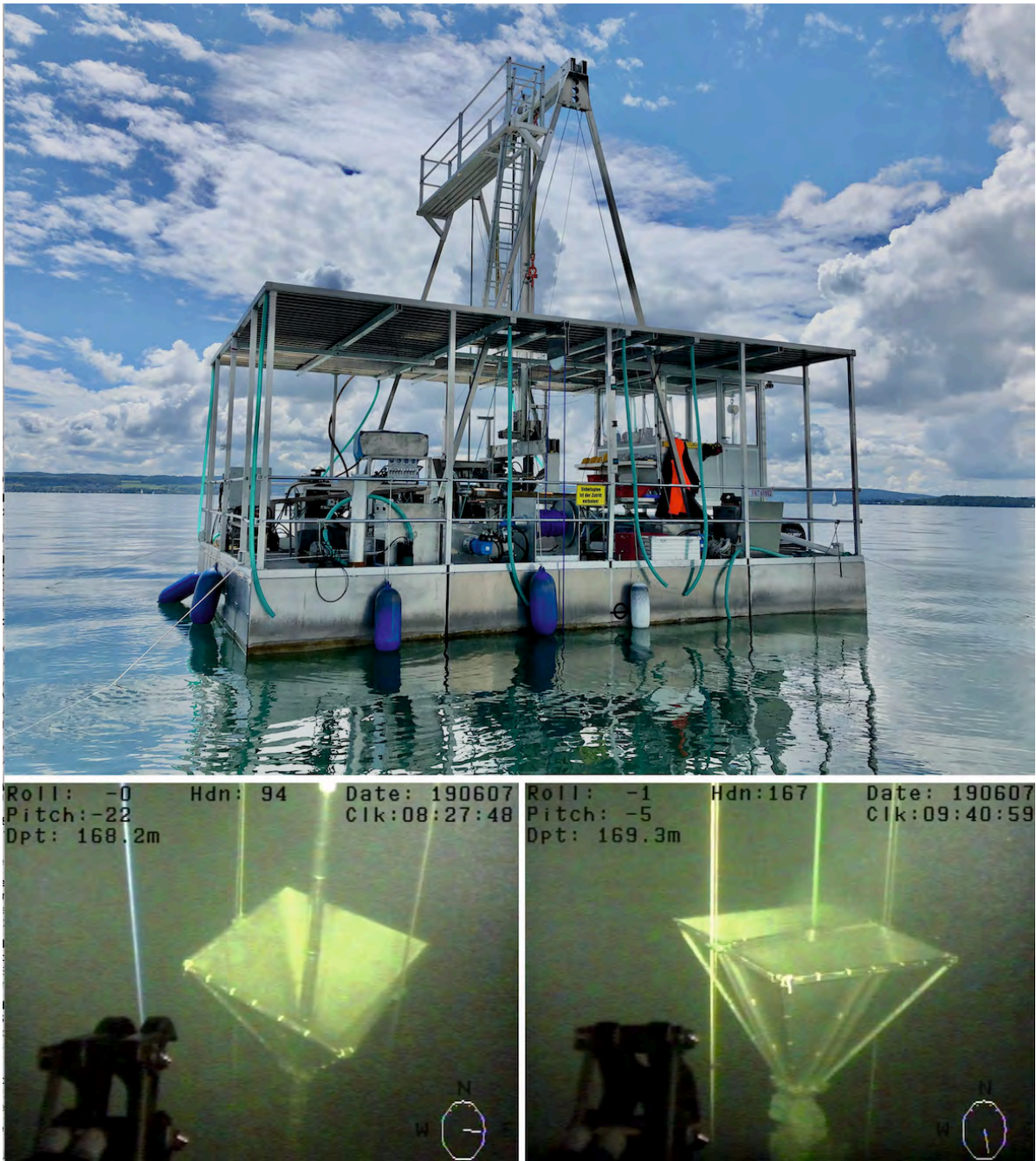
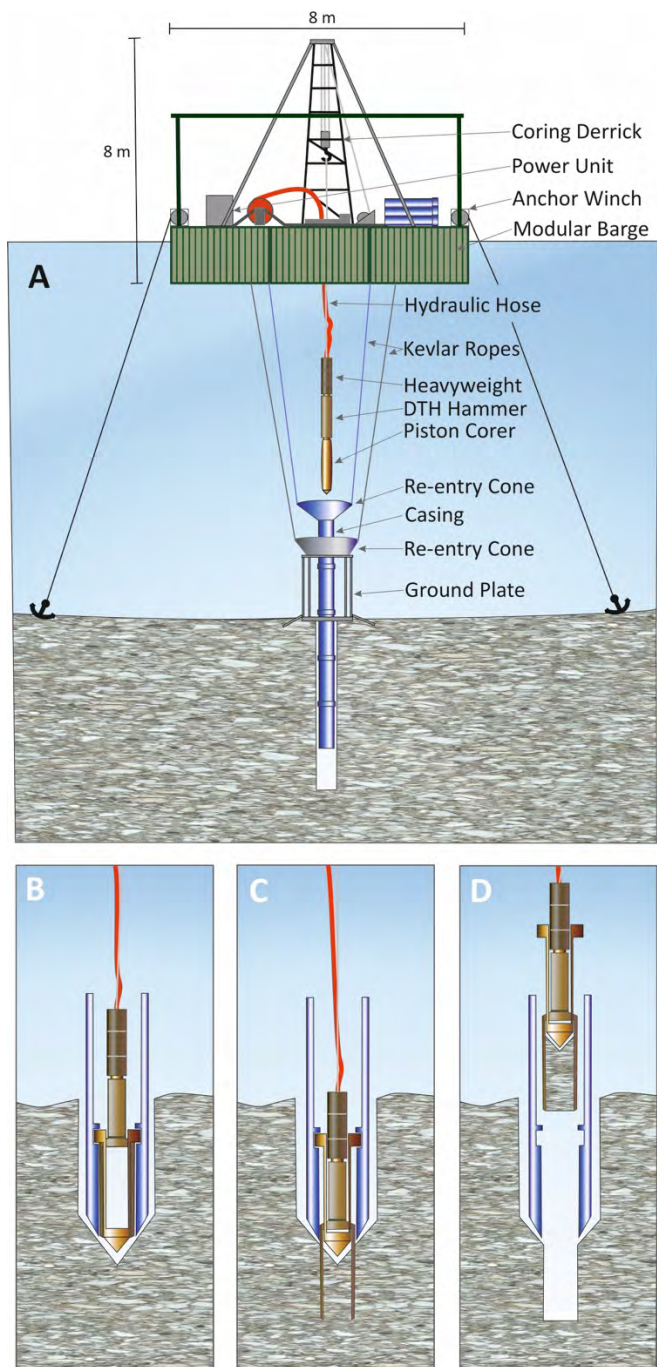


Figure 2: Hipercorig on Lake Constance during coring operations in 2019, upper panel; video stills from R/V Kormoran ROV showing entry of coring assembly in the upper re-entry cone, lower left panel, and re-entry cone with hydraulic hose (green) after coring assembly was lowered into the hole, lower right panel.



445

Figure 3: Scheme of Hipercorig key elements with ground plate set and coring assembly lowered half-way, (A); cartoon of coring operations with coring assembly placed in hole (B), corer hammered into sediment (C), and extraction of coring assembly including new core to platform while casing remains in place (D).



Figure 4: Casing, core barrel and inner liner before set up (left), coring assembly lowered into lake with connection of core barrel with DHT-hammer atop in the rotary unit (middle) and heavyweight rods above the hammer unit hold in place in rotary unit through a make-up plate (right).



Figure 5: Opening of the coring barrel with view on 1.85 m long, core-filled plastic liner (grey) and core catcher (white) (upper); piston in the core-filled upper end of the liner (lower left); piston after core retrieval with sandy sediment from Lake Constance (lower right).

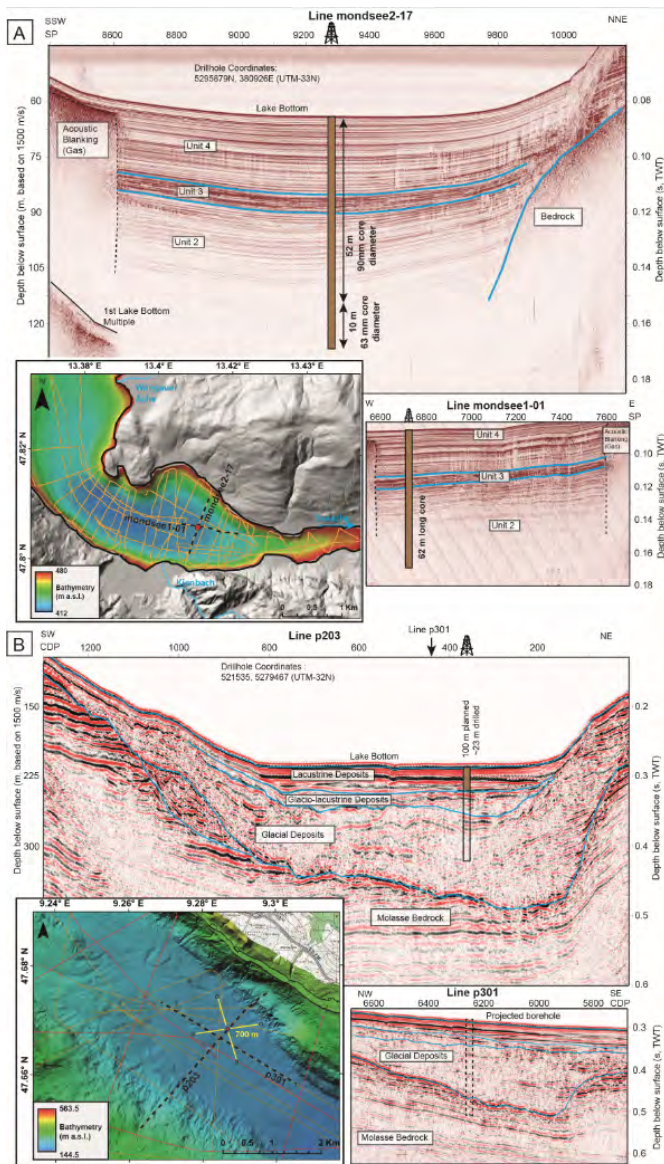


Figure 6: Lakes Mondsee and Constance site survey data and coring sites. A: Bathymetric overview of Lake Mondsee (Austria; data courtesy to Immo Trink), with digital elevation model superimposed. Largest (dis-)tributaries are outlined. Orange lines indicate the 3.5 kHz high-resolution single-channel seismic tracks. Extent of the seismic profiles is shown as dotted black lines. Seismic interpretation follows Daxer et al. (2018), where all details can be found. B Bathymetric overview of Lake Constance, east of Hagnau, with multichannel reflection seismic lines superimposed, recorded in 2016 (red) and in 2017 (orange) using two-chamber Mini GI and GI 210 airguns, respectively (unpubl. Data). Drilling location is given as red dot, with anchor locations in green. Seismic stratigraphic horizons are given as blue lines in Line p201 and p301 (including borehole locations). Extent of the seismic profiles is shown as dotted black lines.

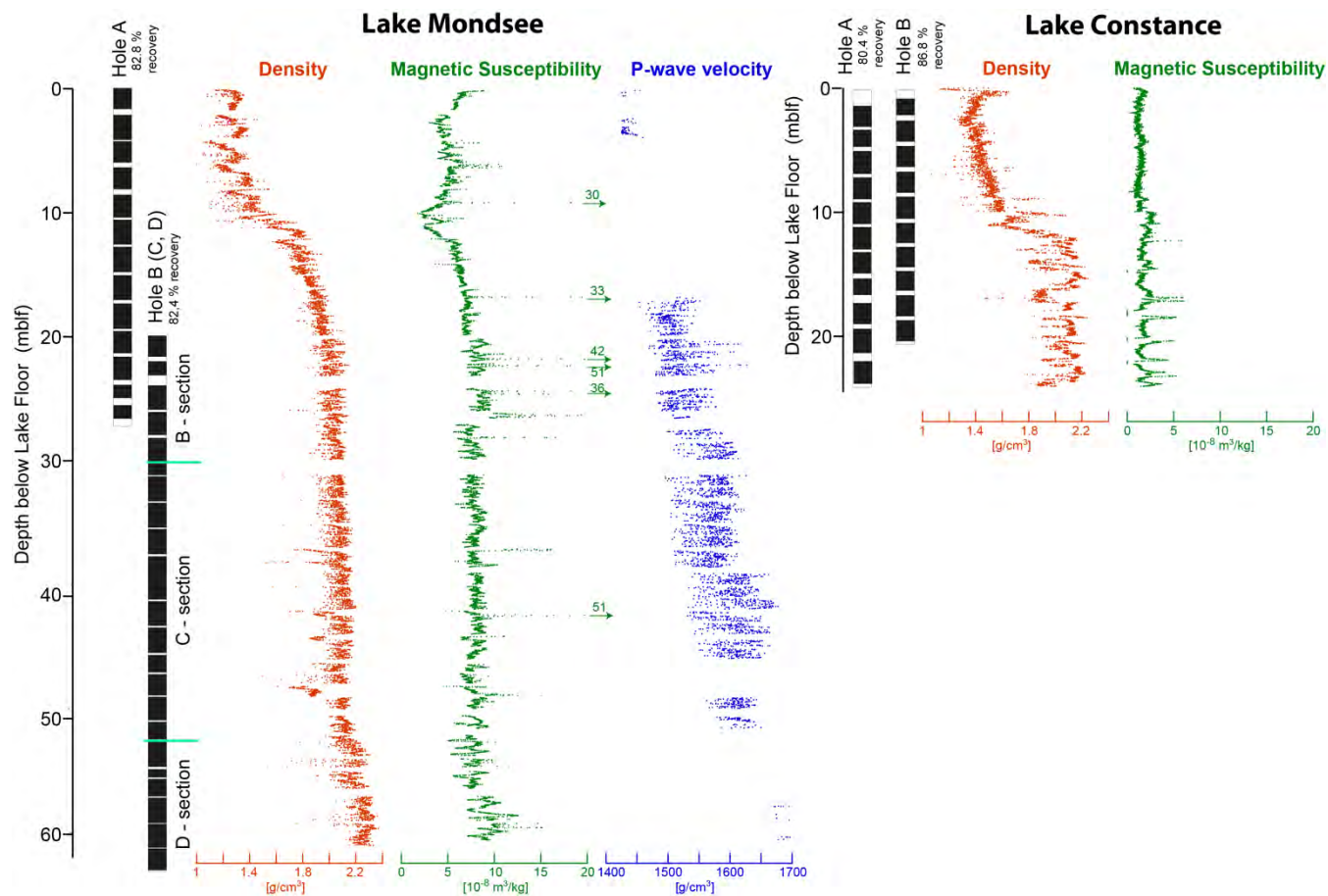
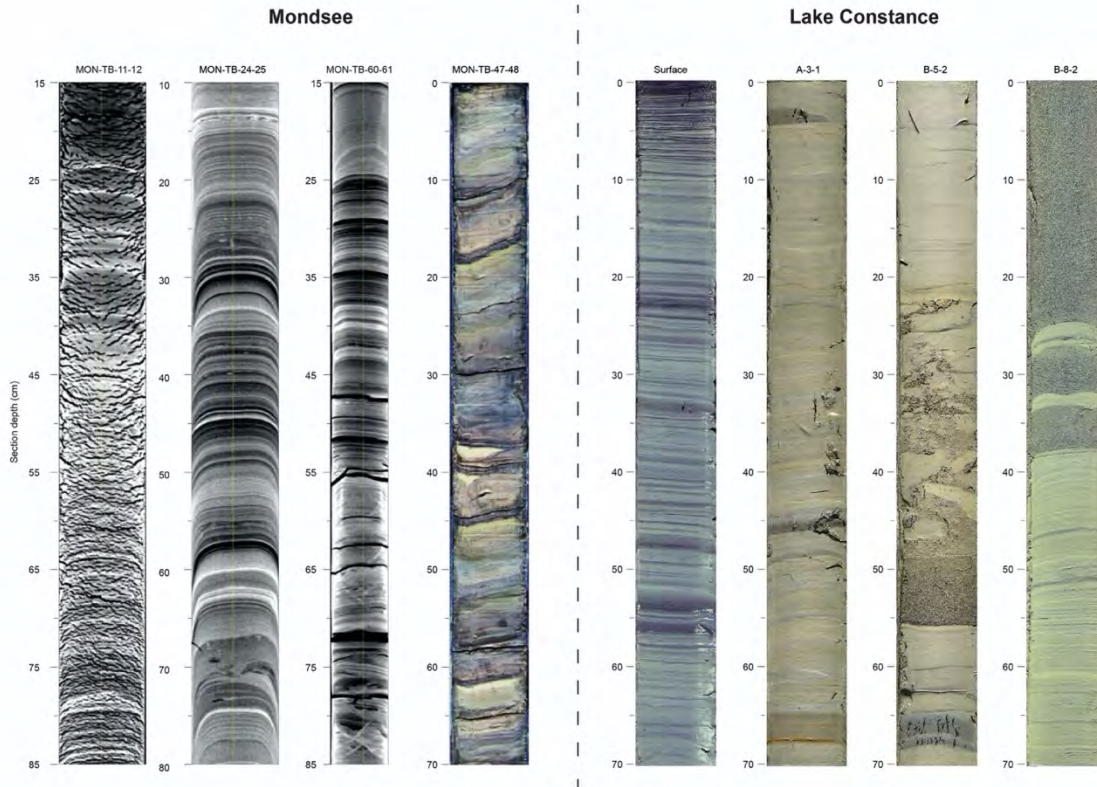


Figure 7: Core recovery (left) and physical property data by MSCL (right) data for the composite cores from Lakes Mondsee (above) and Constance (below).



495 **Figure 8: Left: Examples from X-ray computed tomography (XTC) scan (the first three sections from the left; labeled**
numbers on top of sections indicate subsurface depth range of 1 m core segment) and core photos from Lake Mondsee
(histogram-equilibrated images of depth interval 47.0 – 47.7 mblf) and Lake Constance (4 segments to the right). Note
frequent gas-expansion cracks in XTC-segment Mondsee 11.15- 11.85 mblf, and dense (high CT-value “white”)
conjugated faults at Mondsee 60.80 – 60.85 mblf further discussed in the text.
 500 **Right: 4 examples of line-scan images from core section from Lake Constance composite sections. Depth in cm indicate**
section depths; from left to right: Surface core (0-70 cm meters composite depth (mcd)): Finely layered brown-gray
laminated muds with upcore increasingly darker colors (eutrophication signal); Core A-3-1 (5.75 – 6.45 mcd):
carbonate-rich tan and laminated marls; Core B-5-2 (9.75 - 10.45 mcd): Stiff detrital mud with intercalated sand
 505 **sand layers with intercalated thin graded grey and yellowish silt layers which indicate an annually laminated**
loess/meltwater record deposited during the Oldest Dryas (Wessels, 1998).

Contributions

510 U.H., A.S., and V.W. designed the study; R.N. and V.W. designed HIPERCORIG; R. N. performed coring on Lake Mondsee; R.N. with U.R., A.S. and M.W. led the expedition on Lake Constance; M.S. directed the seismic campaign on Lake Mondsee and investigated Mondsee cores; F.S.A., S.C.F. and S.S. conducted and interpreted seismic profiling and investigated the cores from Lake Constance; U.H., U.R., M.S. and F.S.A. were the primary authors of the manuscript with input from all other co-authors.

Data availability

515 All digital data during drilling operations on Lake Constance and core opening and initial description have been captured using the ICDP Drilling Information System. The full data are available as data publication through GFZ data services website (<https://doi.org/105880/GFZ.X.Y.2020.ZZZ> *to be confirmed!*)

Competing interest

The first author is a member of the editorial board. All other authors declare that they have no conflict of interest.

520